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A Description and Study of Various Types of Concrete Arches

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A DESCRIPTION AND STUDY

OF

VARIOUS TYPES OF CONCRETE ARCHES

BY

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This is to certify that the following thesis prepared under the immediate direction of Mr. L. A. Waterbury, Associate in Structural Engineering, by

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entitled A STUDY OF VARIOUS TYPES OF CONCRETE ARCHES

is accepted by me as fulfilling this part of the requirements for the Degree of Bachelor of Science in Civil Engineering.

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A DESCRIPTION AND STUDY OF VARIOUS TYPES OF CONCRETE ARCHES.

It is the purpose of this thesis to describe and study the various types of concrete arches employed in the construction of bridges, with the intention of determining as well as possible the merits and defects of each type.

During the past ten years the use of concrete as a building material has increased very rapidly. During this same period the use of metal reinforcement has become customary, and this introduction of steel reinforcement is indeed one of the things which has caused the rapid development of the use of concrete, since it has made concrete a suitable material for the construction of a great variety of structures. The bridge builder has not been in the rear but has rather led the advance, both in the use of concrete and in the introduction of varieties of reinforcement. The result has been the production of a great variety of arches differing in kind of arch as well as in reinforcement.

The classification of these arches will necessarily be rather indefinite owing to the various headings under which each arch may be placed. An arch may be classed according to its connection with the abutment - whether hinged or not; according to the shape of the arch ring - whether ribbed or not; or according to the method of reinforcement.

FIXED VERSUS HINGED ARCHES.

An arch is said to have fixed ends if the ring is directly connected with the abutments. If hinges are used between the abutments and the arch ring the arch is called a two-hinged arch. If another hinge is placed at the crown of the arch

it is called a three-hinged arch. Of the three classes, the one almost universally used is the arch with fixed ends. Formerly there was some objection to this type on account of the indeterminate stresses, but since the introduction of the elastic theory and more particularly since its varification by the Austrian Society of Engineers (1890-95), these objections are now seldom raised. The arch with fixed ends is so common that no example will be cited here; all of the arches referred to in the discussion of reinforcement are arches with fixed ends. No two-hinged arches have been built of which the writer knows altho there is no reason why the principle could not be applied to concrete as well as to steel arches.

While the comparative number of three-hinged arches is small, excellent examples may be readily found. An example of the three-hinged arch of plain concrete is the bridge at Brookside Park, Cleveland, O. The span of this arch is 92 feet and the rise is 9 feet. The hinges are made of built up rolled sections with cast iron hinge blocks. Several three hinged arches have been reinforced according to the Melan system. The best example is perhaps the largest. This is the Gruenwald bridge in Munich. This bridge has two arches, each of a 230-foot span. At the time this bridge was built this was the largest span in a concrete arch, either plain or reinforced, in the world. Figure 1 is a section of the Brookside arch.

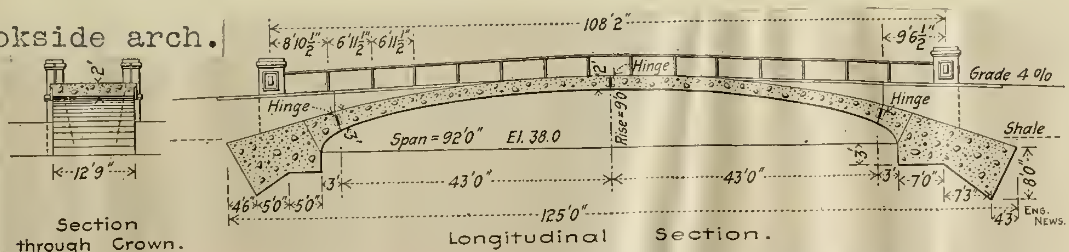

FIG. 1. SECTIONS OF THREE-HINGED CONCRETE ARCH BRIDGE.

Other systems of reinforcement have not been applied to this type of arch, which is a style little used in this country.

The style of hinge has a great effect upon the stiffness of the arch. If the hinge is like that cited above the arch will deflect readily under moving loads. This is undesirable in a railroad arch. For this kind of an arch the hinge is often only a sheet of lead which seperates the two surfaces of concrete. This hinge prevents any cracks due to temperature stresses or to the settling of the arch abutments and at the same time makes a fairly stiff arch.

There are several advantages found in the hinged arch. The one most advanced abroad is that the hinge prevents unsightly cracks appearing upon the settling of the abutments. The thickness of the arch ring may be reduced at the hinges to that necessary to take the direct compression, since there can be no moment at the hinge. The American engineer prefers to spend a little more on the abutments to make sure that they will not settle and take the chance that they will hold the arch without cracks than to spend the same amount on hinges and then have an arch with reduced rigidity and increased deflections. The fixed arch must depend upon elasticity alone to prevent it from cracking on account of temperature stresses. Aside from this however the advantages presented in favor of the three-hinged arch are more than counterbalanced by the resulting disadvantages. With the advent of longer spans it may become necessary to consider the use of the three-hinged arch more seriously but at this time the fixed arch answers

nearly every demand and in the opinion of the writer is the best type.

SHAPE OF THE ARCH RING.

The two classes into which arches may be divided with reference to the shape of the arch ring will be called ordinary arches and ribbed arches. Ordinary arches are those which have a continuous arch barrel having a uniform thickness across the arch at any given distance from the crown. Ribbed arches are those in which the material is concentrated in the form of ribs which are expected to carry the load. Between the ribs there may be a solid web but this is considered to act merely as a bracing for the archribs and not as an arch itself. Figure 2 shows an example of a ribbed arch. Figure 3 is a section of the same arch.

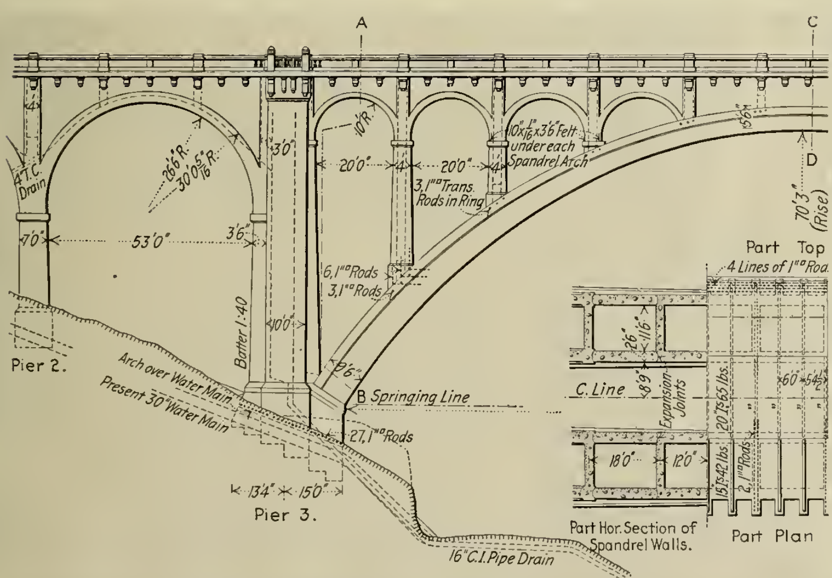

FIG. 2. GENERAL ELEVATION AND PART PLAN OF 232-FT. ARCH AN

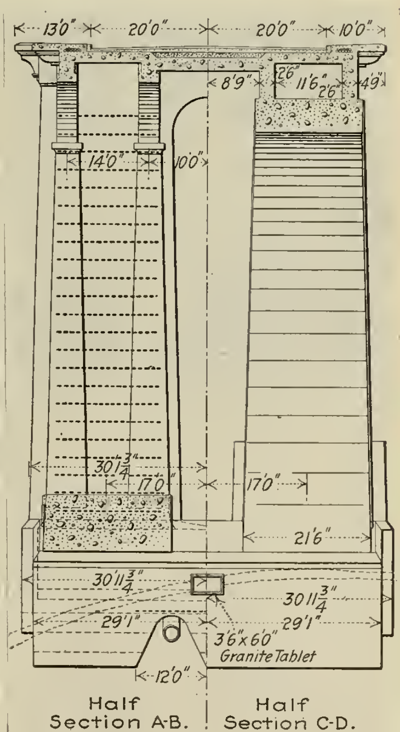

FIG. 3. TRANSVERSE SECTIONS

The advantage of placing the material in the form of ribs is to secure economy of material and increased stiffness. If two arches of the same general dimensions are constructed one of which should have an arch ring with a solid barrel and the other should have the same amount of material in the form of ribs with three times the depth of the barrel, considering that none of the material is used for webs between the ribs, the stress due to direct compression would be the same in both cases while for the ribbed arch the maximum stress due to bending would be one third of that for the other arch, provided both were subjected to the same loads. The relative stiffness of the ribbed arch compared with the ordinary arch would be in the ratio of 9 to 1. Thus the ribbed construction requires less material than the ordinary arch for a given load and a given allowable stress. Since the weight of the arch forms a large part of the load, any reduction in the amount of material required which lightens the load on the arch ring, and further decreases the material needed. However the resulting economy of material may not reduce the cost of the bridge because the forms for a ribbed arch cost more than the simple forms of the ordinary arch. Only a few ribbed arches have thus far been built but they are rapidly coming into general use where the size of the bridge is sufficient to warrant the extra expenditure for the forms in order to effect a saving in the cost or to produce a stiffer arch.

REINFORCEMENT.

The relative merits of plain concrete and reinforced concrete are not easily determined in every case. It is

generally possible to build a structure of plain concrete which will serve the purpose in a more or less satisfactory way. In general however the use of reinforced concrete has so many advantages over plain concrete that one is safe in recommending its use for any arch with the assurance that the resulting structure will fulfill the requirements as well as a plain concrete arch.

The advantages gained by reinforcing concrete with steel, named by Mr. Hill in his book on reinforced concrete, are:

"(1) In long spans the thickness of the ring can be made very much less, thus reducing the dead load and effecting a saving of 50 percent or more in the cost of the ring.

"(2) The load being reduced the thrust is correspondingly less, and the abutments may be made very much smaller.

"(3) Reinforced with steel the working unit stresses may be considerably increased with perfect safety.

"(4) The danger of cracks occuring from any cause can be prevented by the proper distribution of the reinforcing metal.

"(5) Arch rings of such forms and proportions that the bending moments would render them impossible with any ordinary masonry, can be made, and have been constructed of reinforced concrete both easily and successfully.

"(6) Much longer spans are practical for any given set of conditions than could be seriously considered with any other class of masonry."

All of these reasons to the contrary notwithstanding plain

concrete still has its use on many arches which present conditions which would make possible the erection of a stone arch. The fact that it is hard to use reinforcement with any degree of accuracy on small work without using as much concrete as it would take to put up the work without reinforcement is responsible for its extended use on small structures. On the other hand reinforced concrete is used in many places which seem to present ideal conditions for the use of plain concrete.

Arches without Reinforcement.

The plain concrete arch is here considered as an arch whose ring is made up of plain concrete either as a monolith or in parts but which does not contain any reinforcement. The reinforcement may be used in the abutments, piers, spandrel walls, spandrel arches, or in the bridge floor itself. The arch proper is sometimes built up in transverse segments placed symmetricly about the center line of the arch, in order to prevent the centers becoming distorted on account of unequal loading. This kind of an arch ring is very similar to the voussoir arch built of stone. It demands the same treatment in design and in comparing it with stone the advantage of one over the other appears from a summation of unit cost of stone on the one hand and of concrete on the other.

The most notable railroad arch of plain concrete in the United States is probably the bridge of the Illinois Central across the Big Muddy near Carbondale, Ill. It consists of three arches, each of a span of 140 feet and a rise of 30 feet. Figure 7, page 20 is an illustration of this arch.

A concrete arch is now being built across the Wissahicken

Creek in Philadelphia. This is the largest plain concrete arch in the world and is 22 feet greater in span than the largest stone arch in America. Its span is 232 feet and the rise is 70 feet 3 inches. The arch ring is made up of two ribs not directly connected with each other. The bridge floor is carried on spandrel arches and is the only connection between the ribs. When the arch ring is ribbed, the ribs are usually connected in the ring by a thin slab at least. See Fig. 2, page 4.

Reinforced Arches.

The first use of the metal reinforcement was made for the purpose of strengthening the concrete but no attempt was made to study the matter carefully to see where the reinforcement would be most efficient. The use of reinforcement gives so much additional security at a small outlay that now the designers are endeavoring to secure the most advantageous location of the metal and the most efficient type of reinforcement.

There are now in use a very great number of so-called systems of reinforced concrete, some of which differ only in the form of reinforcing bars, while some differ also in the method of distribution of the reinforcement. However, all of the systems can be classed under one of the following three types or as a combination of two or more, viz., network, beams or rods. These three types will now be described.

NETWORK REINFORCEMENT. The method of reinforcing concrete with a steel netting is usually called the Monier system after its founder, Jean Monier, who was the first to apply any method of reinforcement to arch construction. In 1865 he discovered that a netting of wire made his flower urns stronger and

in 1867 he used this netting in the construction of arch bridges with great success. It was not until 1884 that he had his system patented in the United States. His chief claim in this patent is: "As an article of manufacture, an integral element of construction composed of a metal skeleton comprising longitudinal bars or rods and transverse ribs secured by ligitures of metal and a covering of cement in which said metal skeleton is embedded, all constructed and arranged substantially as set forth." In general practice this skeleton has as many bars extending in one direction as in the other, and all of the bars are of the same size. These bars are small so that the whole reinforcement consists of a screen whose mesh is seldom larger than 3 inches.

At first the network extended only along the intrados but afterwards the haunches of the arch were reinforced for a little way along the extrados, and finally the netting was carried clear across both the extrados and the intrados. No reinforcements were used in the spandrel walls or the abutments, which parts were not necessarily of concrete but were often of brick or stone masonry.

This system of arch construction has been used very much in Europe for light road bridges but has seldom been used in the United States without variations. One reason for this is that concrete arches were not built here until other systems had been developed which were more favorably received. Its use has been largely confined to small spans altho several have been built with spans greater than 100 feet and one, the bridge at Weidhofen, Austria, has a span of 140.2 feet.

An examplo ofthe Monier idea as applied in the United States is found in the bridge of the Southern Railway near Austell, Georgia. This bridge consists of four arches, each of 70-foot span and 20-foot rise. The reinforcement consists of one and one-quarter inch barsplaced 12 inches on centers and one-half inch transverse bars placed 3 feet on centers. The reinforcement is placed along the extrados as well as along the intrados. The thickness of the arch at the crown is 3 feet 4 inches . This seems to be a good ways removed from the original idea of Monier netting but it satisfies the claim of the patent. This is an exceptional Monier arch and if this description is to be adhered to as a good example of this construction, then there are a good many infringements on the Monier patent in existence.

STEEL BEAM REINFORCEMENT. The next method of reinforcement was the result of the idea that the transverse reinforcement was superfluous. This method substituted a solid rolled beam for the longitudinal reinforcement and dispensed with the transverse reinforcement all together, except in the abutments as a fastening for the longitudinal beams. Prof. Jos. Melan, of Prague was the originator of this system which he had patented in the United States in 1893. His principal claim is: "A vault or arch consisting of abutments, beams or girders, arch ribs rigidly connected with said abutments, beams or girders, and a filling in of concrete or the like between said ribs substantially as described"

The usual conctruction of the Melan arch in the American practice has dispensed with the only transverse reinforcement-

that at the abutments.

Herr Fr. von Emperger introduced the construction of the Melan arch in America and after building a number of arches with rolled beam reinforcement, which is the method used in the original Melan arches, he modified the type by replacing the rolled beam with a latticed girder. By making the beam in this way he was more nearly able to place the metal where it would do the most good - that is, near the intrados and the extrados . The latter type of arch is almost always spoken of as the Melan arch and nearly all of the Melan arches which are now constructed are of this type.

Examples of the Melan arch are plentiful in the United States, of which over one hundred arches have been built in this country. An example of the use of the cambered I beams is found in the 100-foot arch foot bridge at Stockbridge, Mass. This bridge is only 7 feet wide but it shows very plainly the application of the true Melan principle. This is one of the first arches built by Emperger.

A good example of the latticed girder type of construction is the bridge at Topeka, Kans. The largest span of this bridge is 125 feet, there are two other spans of 110 feet, and two of 95.5 feet. The width of the bridge is 40 feet. Figure 4 is an example of the Emperger variation of the Melan principle.

BAR REINFORCEMENT.

The Thacher Type. The next step in the development of reinforced arches was to discard the web of the girder and use plain rods for the flanges. This was first done by Edwin

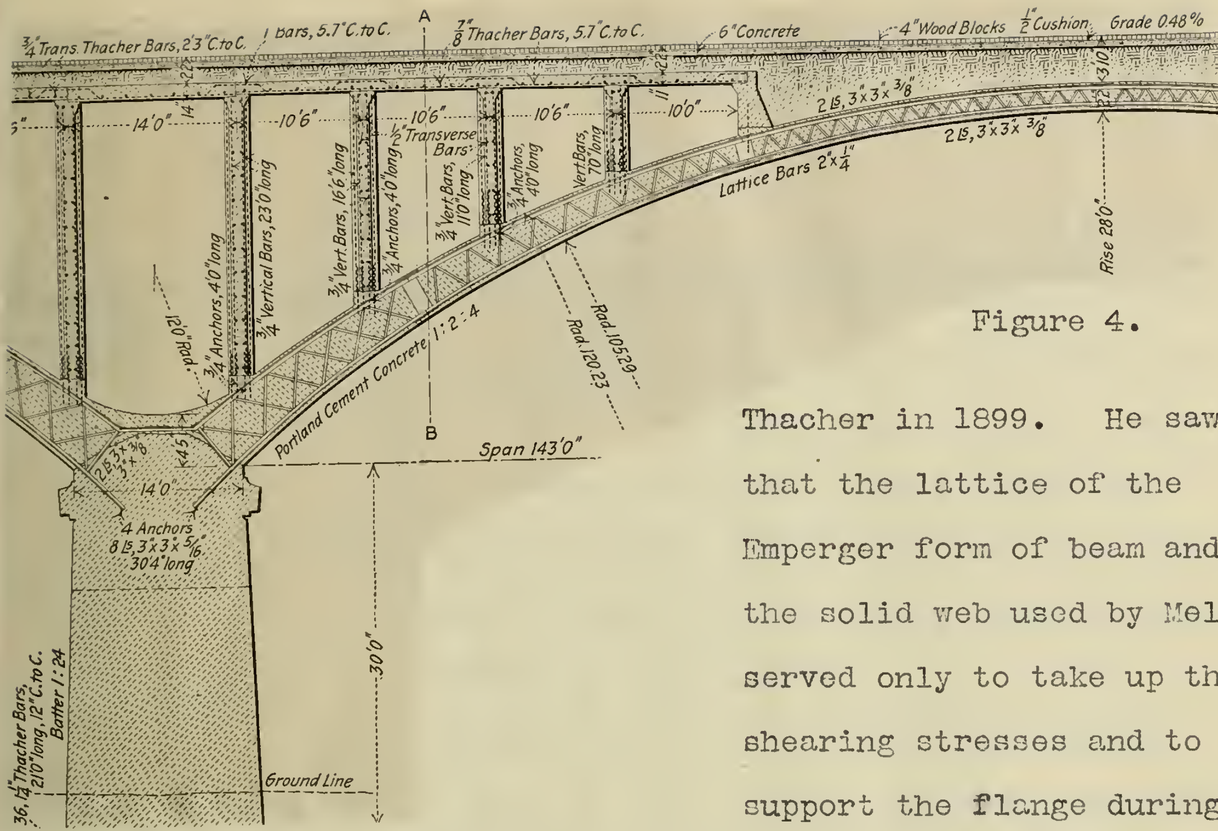

Figure 4.

Thacher in 1899. He saw that the lattice of the Emperger form of beam and the solid web used by Melan served only to take up the shearing stresses and to support the flange during construction. As the shearing stress is small and can be safely born by the concrete without reinforcement, and since with a little care the flange reinforcement could be properly placed, he dispensed with the web altogether and used reinforcement along the intrados and the extrados only.

In the patent for this system issued to Mr. Thacher the claim is as follows: "The combination, with abutments and a concrete arch spaning the intervening space, of a series of metal bars, in pairs, one bar of each pair above the other near the intrados and the extrados of the arch and extending well into the abutments, each bar of a pair being independent of the other, and each bar being flat and provided with projections substantially as described."

The reinforcing bar originally used by Mr. Thacher was a flat steel bar provided with rivets with tall heads which

were to give a more effectual bond between the concrete and the steel. The reinforcement which he uses at present is a rolled steel bar with the projections rolled on it.

This form of concrete steel construction for arches is now used more than all others combined in this country. Plain bars, and other reinforcing bars which have been patented, have been more extensively used on this system than either of the Thacher bars. Mr. Thacher is the head of a construction company which controls the Monier, Melan, Emperger, and Thacher patents and is probably the best known engineer on reinforced concrete arch construction in America.

Examples of the Thacher system are numerous and varied. Nearly every concrete arch in this country which has reinforcements uses this form of construction. The Danville, Ill. bridge of the Big Four Railway across the Salt Fork is an excellant example of this type.

<u>Luten Type</u>. Mr. Thacher is not the only one who has developed ideas using plain bar reinforcement. A short time after the Thacher system was patented, Danl. B. Luten received a patent for another system using plain bars. Mr. Luten has his idea very well protected by a number of claims but the following claim states his system very well: "An arch having embedded therein a plurality of tension members passing alternately across the rib, said members being low at the crown and high at the haunches and each of said members passing across the rib at differant points from the others, a pavement extending across the bed of the stream between the abutments and the side walls, ties embedded in said pavement and extending from abut-

ment to abutment substantially as described." There are other claims which allow the tension members to be low in the haunches and high in the crown. He also has claims which allow the use of the system as described omitting the pavement.

Mr. Luten does not consider that it is always necessary that the centerline of the arch ring should coincide with the line of resistance. He uses a segment for the curve of the extrados and for the introdos he uses a curve found by bisecting the radial distance between a circle and an ellipse drawn through the crown and the springing line of the proposed arch. See figure 5. He has found that the line of resistance will

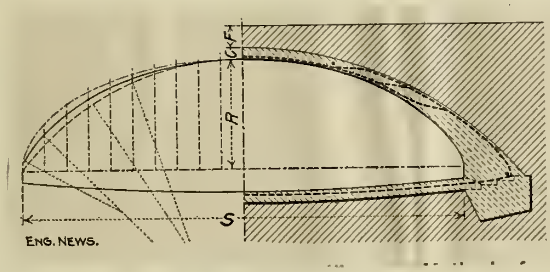

Figure 5.

come very close to the ring thus constructed. However he believes in letting the reinforcement take little tension and makes no further investigation of the line of thrust. In defence of this policy he says that he has built several hundred arches by this method and has never had a sign of failure.

The arches built by Mr. Luten have been very successful in competing with steel structures of similar requirements for the same location. An example of this is the highway bridge at Peru, Indiana. This bridge is 700 feet long and is composed of seven arches with spans varying from 75 to 100 feet.

The rise of these arches varies from 13 to 15 feet. The roadway of this bridge is 35 feet in width. The bid for the construction of this bridge was the lowest of several, and all of the other bids were for steel structures. See figure 6

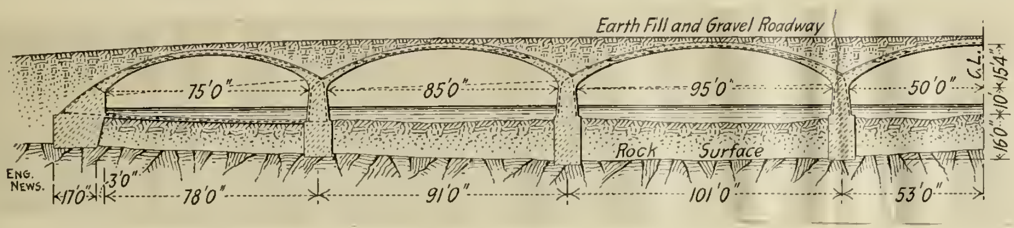

Figure 6.

for a longitudinal section of the bridge.

Discussion of Reinforced Arches.

In criticising the various systems the distribution as well as the effeciency of the reinforcement must be noted. Transverse reinforcement may be needed to distribute the load across the arch ring. If the ring is wide and thin and there is little or no filling between it and the applied concentrated load then the advantage of transverse reinforcement becomes apparent. However if there is quite a depth of earth fill or deep spandrel arches the load will be sufficiently distributed and transverse reinforcement will not be necessary.

The longitudinal reinforcement may be either in tension or compression. If the center line of the arch ring follows the line of resistance there will be no tension on either side of the ring and the only stress to be taken by the steel will be compression. Steel is not as economical as concrete when used to resist compression therefore it should not be used primarily for that purpose. The reasons for placing longitudinal rein-

forcement in such a ring were stated above under the subject of Reinforcement.

The netting is the only type of reinforcement in which the transverse reinforcement occurs, although the Thacher type is often modified by using transverse bars as well as longitudinal reinforcement. With the netting reinforcement there is as much transverse reinforcement as there is longitudinal, and while the relative importance of the two reinforcements may vary it is seldom considered that such a quantity of transverse reinforcement would be necessary. There have been many objections raised against this style of reinforcement and some of them have been well taken. The difficulty of placing the concrete properly without disturbing the network of reinforcement has forbad the use of a concrete or mortar of less rich proportion than 1 to 3. The reinforcement being so flexible that it is considered unwise to introduce any form of course aggregate at into the mortar. This of course makes the cost higher without giving any additional strength in return.

Since the only use of the transverse reinforcement is to distribute the load over the ring there is no reason why it should not be concentrated in the intrados where it would take tension instead of placing it on both sides of the arch ring.

The Monier system should not be too severely criticised for it served its purpose which was to make the concrete stronger without attempting to distribute the reinforcement according to theory.

The first attempt to place the reinforcement where it would do the most good was made by Melan when he introduced a rein-

forcement of rolled beams. There are a good many objections to the simple rolled beam used for the reinforcement of a concrete arch. If a solid beam of constant cross section is used the metal cannot be placed where most needed unless the arch ring is also of constant cross section and still the reinforcement is not so much needed on the side of the ring which bears the most compression as it is on the side which might be in tension. Of course the ring will probably follow closely the line of resistance and in that case there will be no tension and the reinforcement would serve merely to strengthen the whole fabric and allow the use of higher working unit stresses. These beams are hard to handle on the work and more expensive than the plain rod reinforcement.

The use of the lattice girder permits the reinforcement to be placed where it is desired, but the lacing is of little use since it resists only the shearing stress which the ring of plain concrete is able to withstand. The criticism of shop cost and difficulty of handling holds true for the lattice girder as well as for the plain beam. However this type of reinforcement has one advantage over the plain bar, in that it will stay where placed and cannot be misplaced by a careless workman.

The plain bar reinforcement is very similar to the latticed construction of the Melan type but it eliminates the lattice and leaves the bar unsupported and allows the ring itself to to take up the shear. The bar is just as firmly fixed in the concrete as the latticed girder and the cost in the shop and on the work is considerably less. If a proper rod is used the

the only objection to this system is that a careless workman may misplace the rods. The writer believes however that the systems using the plain bar reinforcement would be more effective if they would use a little transverse reinforcement instead of none at all.

Besides applying the bars to the ring Mr. Luten uses them to resist the thrust of the arch. By tieing the abutments together with metal placed in a concrete pavement he lessons materially the weight of the abutment and this is a special economical advantage in doubtful foundation soil. Mr. Luten's design seems bold in some ways but the seven hundred arches built in this way stand without a failure to prove it rational.

In general, the use of reinforcement in arch work is merely to strengthen the concrete in order that it may take a higher stress and few designs can be found which allow the reinforcement to take any tension. The method which accomplishes this most economically is to be prefered. The plain bar seems to do this most successfully and the Thacher and Luten systems each find their proper field. The Thacher system applys best to large and heavy work such as railroad arches. The Luten method is most successful when applied to highway or interurban traction bridges - that is its economical features are most beneficial on that kind of construction.

CONCLUSION.

The following are the writer's conclusions, some of which have already been stated.

1. For small and moderate sized arches with a good foundation, the arch with fixed ends will probably be better than and

cheaper than a two-hinged or three-hinged arch.

2. For arches to be erected upon a somewhat yielding foundation, the hinged arch may be advisable as protection against cr cracking if the abutments settle, but for such arches simple hinges, such as those formed by the insertion of a sheet of lead, are preferable to more intricate hinges, both on account of the simplicity of construction and on account of the rigidity of the structure.

3. For small arches, the ribbed type of arch is not likely to be as economical as the ordinary type, and for large arches there is not likely to be a very great saving in cost by using the ribbed arch, but if the cost of the ribbed arch is no greater than that of the ordinary type, it may be the more desirable on account of its greater rigidity and because it is likely to lend itself to artistic treatment.

4. For small arches, plain concrete is probably more economical than reinforced concrete.

5. For large and moderate sized arches, reinforced concrete is preferable to plain concrete not primarily on account of cost but because it is a better type of construction, although it is probable that the reinforced arch will be more economical than the plain arch for large spans.

6. The best type of reinforced arch for bridge work is probably the bar type since it permits a better distribution of the reinforcement and by the use of transverse bars any ratio of transverse to longitudinal reinforcement, which seems desirable may be had.

Figure 7.